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ORIGINAL PAPER

Effects of rainwater harvesting on herbage diversity and productivity in degraded Aravalli hills in western India

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Abstract: Over-exploitation and rural growth have severely damaged native vegetations of Aravalli hills in Rajasthan, India. This study was conducted to evaluate the effects of different restoration practices (i.e., rainwater harvesting (RWH) and planting of tree seedlings) on improvement in soil water and nutrients and growth and biomass of herbaceous vegetation. Contour trench (CT), Gradonie (G), Box trench (BT), V-ditch (VD) and a control were imposed on 75 plots (each of 700 m^2) in natural slope gradient defined as <10%, 10%–20% and >20% slopes in 2005. Each plot had three micro-sites of 1-m^2 at up (USP), middle (MSP) and lower (LSP) part of the plot for observation in 2008. The existed gradient (due to soil texture and topographic features) of soil pH, EC, SOC, NH_4-N, NO_3-N and PO_4-P in June 2005 between >20% to <10% slopes were decreased in 2008 after applying RWH techniques. Such improvement in soil status promoted vegetation growth and biomass in higher slope gradients. Soil water, species diversity and herbage biomass increased from USP to LSP, and RWH techniques had positive role in improving SOC, nutrients, vegetation population, evenness and growth at MSP. Despite of lowest SWC, regular rain and greater soil water usage enhanced green and dry herbage biomasses in 10%–20% and >20% slopes, compared with <10% slope. The highest diversity in CT treatment was related to herbage biomass, which was enhanced further by highest concentrations of SOC and PO_4-P. Further, CT treatment was found to be the best treatment in minimizing biomass variance in different slopes. Conclusively, soil texture and topographic features controlled soil water and nutrients availability. Rainwater harvesting techniques increased soil water storage and nutrient retention and also enhanced vegetation status and biomass by minimizing the effects of hillslopes. Thus depending upon the site conditions, suitable RWH technique could be adopted to increase herbage biomass while rehabilitating the degraded hills.

Keywords: herbage growth and biomass; hillslopes; soil nutrients; soil water dynamics; vegetation diversity

Introduction

Roughly 50% of the earth's terrestrial surface is grazed by large herbivores (Frank et al. 1998). Such grazed lands are the backbone of profitable forage–livestock systems that contribute substantially to the rural economy in dry areas. In addition to the traditional practices of farming, agronomy, conservation, ecology and landscape development, the new approaches for rescuing the degraded rangelands include reducing uses of fertilizers and pesticides (Watkinson et al. 2001; Krueger et al. 2002). Within these approaches, maintaining biodiversity is an important aspect as plant diversity positively influences primary production (Tilman et al. 1996; Hector et al. 1999), provides stability in response to disturbance (McNaughton 1977; Frank et al. 1991), improves soil nutrient retention (Reich et al. 2001) and reduces invasion by exotic species through complete use of resources (Naeem et al. 2000; Tracy et al. 2004). However, most of these managements of increasing plant species diversity to increase herbage production can improve yield stability and reduce soil nutrient losses, which are associated with the increasing irrigation and fertilizer uses.

Production of biomass is directly linked with availability of water and nutrients in the soil, which is main limiting factor particularly in overexploited and degraded hills like Aravalli in India. Further, limitations of soil water and nutrients are aggravated in upslope position due to existing slope gradient in the slopes of the hills, which needs to be minimized by conserving soil and water. Existence of a complex eco-geomorphological system composed of a multitude of vegetation patches distributed at random on the hillslope, where the presence of different surface conditions on the soil had a sizeable influence on hydrological and erosive behavior (Sinoga et al. 2010). Thus increasing vegetation cover by conserving soil water and nutrient (Gregory 1989) may be the best option to reduce run-off losses and to

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restore the degraded hillslope. Rainwater harvesting (RWH) is useful in conserving soil and water resource, enhancing nutrient mobility, improving soil moisture storage and prolonging the period of moisture availability in soil (Boers et al. 1986; Cater et al. 1991; Wani et al. 2002). This may also minimize soil water and nutrients gradients in hillslopes by enhancing these soil resources along the RWH structures. The improvement in soil water and nutrient in higher slopes may enhance vegetation diversity and productivity, which may be helpful in restoration and rehabilitation of the degraded hilly rangelands. In many sites, specific RWH structures are used for conserving soil and water and enhancing growth of tree seedlings. Some of these practices are contour trench, gradonie, box trench, staggered trenches and V-ditches. However, these practices have not been sufficiently evaluated in terms of reducing/minimizing the variability in soil water and nutrient in hillslope and improving vegetation diversity and herbage productivity.

Therefore, the objectives of the present study were to explore: (1) the effect of rainwater harvesting (RWH) techniques on improvement in soil water and nutrients availability in different slopes, (2) the effects of RWH techniques on vegetation diversity and productivity in rehabilitating hilly rangelands.

Materials and methods

Study sites

The experimental site (23º25'27.0"–23º25'43.4" N, 74º 24'00.5"–74º 24'23.1" E, 248 – 320 m a.s.l.) is located about 17 km southwest from Banswara in the southern part of Rajasthan, and bounded in the north by Udaipur, the northeast by Chittorgarh and west by Dungarpur districts of Rajasthan. The district is bounded in east and southeast by Madhya Pradesh and in the southwest by Gujarat states. Soils are black, brown and stony ranging from shallow in steep slope area to deep in the pediment. The variation in temperature is from 4 ºC in January to 42 ºC in May. The mean annual minimum temperature is about 15 ºC and annual maximum temperature is about 33 ºC. Average annual rainfall from 1993 to 2006 was 1 055.4 mm with 54 of rainy days. However, total rainfall in 2008 was 562.5 mm (in 29 events), out of which 496.83-mm rainfall was during June to October 2008. Average rainfall was 101.0 mm, 192.3 mm, 129.5 mm and 74.0 mm in June, July, August and September 2008, respectively (Fig. 1a).

Slopes of the site ranged from 3% to 53%, which were categorized into steep (> 20%), medium (10%–20%) and gentle slopes (<10%). The steep slope area was covered with pebbles/gravels of varying size and associated with *Lantana camara* bushes. Medium slope area had light textured sandy loam soils (30–40 cm deep) and was dominantly covered by *Prosopis juliflora* and the scattered bushes of *L. camara*. Soil texture in gentle slope area with *P. juliflora* and *L. camara* bushes was from loamy to clay loam from shallow to deep in soil depth. Soil is from dark brown to black in color in steep and gentle slope, whereas it is from light brown to light red in color in medium slope. Gravel content was ranged from 78.4% to 87.7% of total soil and dominated in >20% slope. Sand content was ranged from 7.5% to 17.3% of total soil and the highest was in 10%–20% slope. Silt and clay contents were greater in <10% and >20% slopes than those in 10%–20% slope. Soil pH was from acidic to slightly alkaline in reaction (6.34 to 7.02). Soil organic carbon (SOC), available NH_4-N, NO_3-N and PO_4-P were 0.760%, 22.15 mg·kg^{-1}, 2.50 mg·kg^{-1} and 4.51 mg·kg^{-1}, respectively in June 2005 (Singh 2008). The shrubby vegetations i.e., *P. juliflora* and *L. camara* were removed sequentially to facilitate rehabilitation work and development of natural vegetations.

Experimental design

A total of 75 plots of 700 m^2 area were laid in the hilly areas with <10% slope, 10%–20% slope and >20% slope. Each plot was separated by an individual boundary of bund cum trench (2025 cm^2 cross section area, 45 cm ×45 cm) to avoid water intrusion from the other plots. The plots had a rainwater harvesting structure of 30 running meters length (Singh 2008) except for the control plots. Contour trenches (CT) were excavated at different contour levels to control soil loss and collect run-off water from upslope area to enhance soil water status and were 2025 cm^2 in cross section (45 cm × 45 cm). Box trenches (BT) were intermittent trenches of 2-m length (15 numbers) with cross section area similar to that in the contour trench. V-ditches (VD) were across the contour with 1800 cm^2 cross section area as calculated by following equation:

$$S = (120W \times 30H)/2 \quad (1)$$

where, S is the section area, W the width, and H is the height of the cut. The vertical (height of 30 cm) cut was downside of the slope. Gradonie (G) ditches also had 1 800 cm^2 of cross section area ((30×120)/2), but the vertical cut was upside of the slope to reduce run-off velocity of water and to prolong the time of water movement in soil. In all the treatments, the excavated soil was heaped towards the down slope. The control plots were without RWH structures for comparison with the RWH treated plots. Most of the RWH structures are concentrated in middle portion of the plots and stretched in two to three fragments, except for in BT treatments in which 15 trenches were distributed intermittently throughout the plots. Experiment was laid in a complete randomized block design. There were 75 plots with five rainwater harvesting treatments in five replicates, which were distributed in three slopes covering an area of about 17 ha. Three micro-plots (micro-sites), each area of 1 m^2 was laid at the centre of upper (USP), middle (MSP, downside of RWH structure) and lower (LSP) part of the above-mentioned plots.

Data recording

Shallow soil depth in steep slope area limited us to collect soil samples in soil layer of 0–40 cm to maintain similarity in all the slopes. Initial soil sampling and soil texture analysis were done in June 2005. For the present study, soil sampling was done in

June 2008 before monsoon. Soil samples were collected from three micro-sites and homogenized to form a composite sample for each plot. The soil samples were dried and passed to a 2-mm sieve for separation of gravel and soil. Soil pH and soil organic carbon (SOC) were determined using standard procedures (Jackson 1973). Available nitrogen (NH_4-N and NO_3-N) was determined after 0.5-M K_2SO_4 extraction using ultraviolet-visible spectrophotometer Model Shimadzu-1650PC. Extractable phosphorus was determined by the Olson's extraction method (Jackson 1973) using above-mentioned spectrophotometer. For soil water content (SWC) determination, the collected soil samples from each micro-site were put immediately into polythene bag to avoid water losses during transport to laboratory.

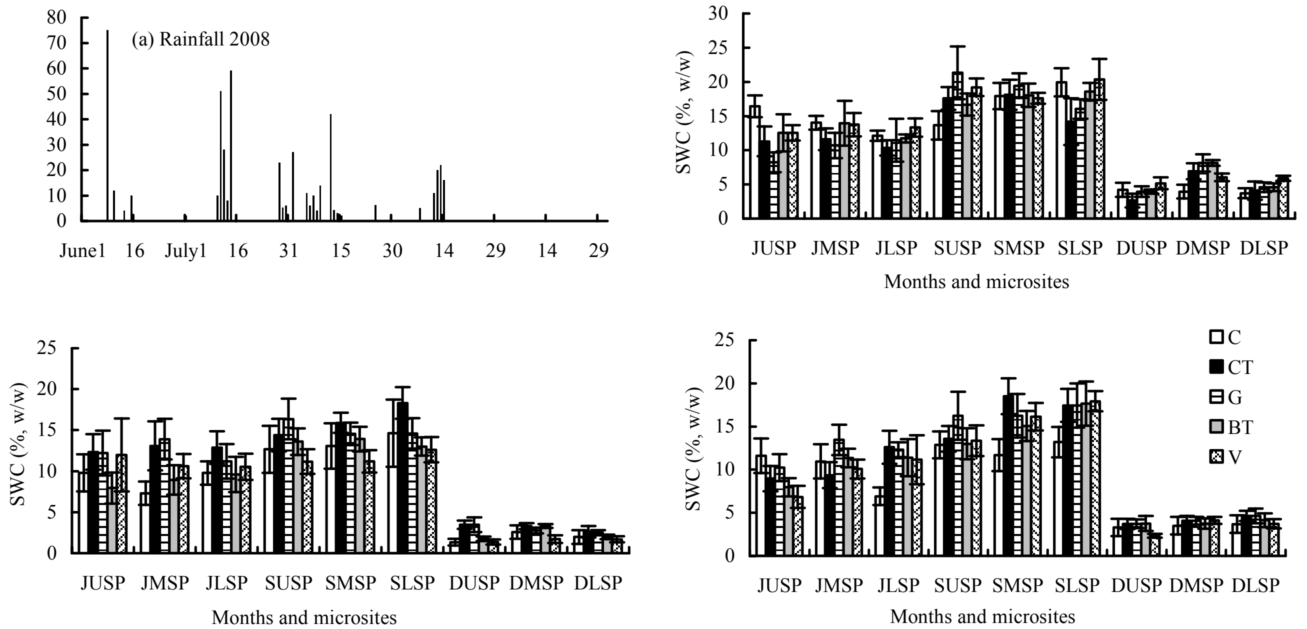

Fig. 1 Rainfall from June to October in 2008 and variations in soil water content in July (J), September (S) and December (D) 2008 in different months influenced by micro-site, slope and rainwater harvesting treatments in Aravalli hillslope. USP, MSP and LSP are upper, middle and lower sampling position (microsites) within a plot in July (J), September (S) and December (D). Error bars are ±SE of five replications.

Soil sampling for SWC determination was carried out 3 times i.e., in July, September and December 2008 from the above-mentioned micro-sites to observe changes in soil water content throughout the season and the micro-sites (gradient in a plot). Soil water content was estimated by oven drying of the samples at 110 °C for constant weight. Soil water depletion during vegetation growth was calculated as percentage decreased in SWC from September (highest soil water content) to December for observing a trend relation between soil water use and herbage growth/biomass. A photosynthetically active radiation (PAR) was measured at above-mentioned micro-sites in September 2008 using portable CI-301 and CO_2 gas analyzer. Above and inside vegetation (at soil surface) PAR was measured to monitor change in PAR at ground surface because of the growing vegetation.

The vascular vegetations above ground from micro-sites of 1-m^2 area were clipped just above the surface from the micro-sites and sorted to species in October 2008. Vegetation was identified as per taxonomy classification using standard literatures (Shetty et al. 1993). These species were counted manually and categorized into number of species and their population. Green herbage biomass was recorded using electronic top loading balance after separating individual species. Dry mass of individual species was recorded using above-mentioned electronic top loading balance after drying the sample at 80 °C in an electric oven to a constant weight. This dry mass is referred as species biomass. Summed dry mass of all the aboveground living vascular plants from a harvest is dry herbage biomass and it is considered as above-ground primary production. Various diversity variables viz., species richness, diversity, evenness and dominance were calculated following standard literatures (Shannon et al. 1963; Misra 1968).

Statistical analysis

The data collected were statistically analyzed using SPSS statistical package version 8.0 for "Windows 2000". Soil nutrient and soil water depletion were analyzed using a two-way ANOVA. Above-mentioned plant parameters were the dependent variables. Slope and rainwater harvesting treatments were the fixed factors. Since soil water content of June, September and December 2008, green and dry herbage biomasses, species richness (R), vegetation diversity (H), species dominance (D) and species evenness (e) were recorded/ calculated from three micro-sites in a plot, these data were analyzed using repeated measures ANOVA. Different micro-sites in a plot were considered as the tests of within- subjects effects, whereas slope and rainwater harvesting treatments were tests of between-subject effects. Percentage of

soil water was on square root transformed data before statistical analysis to reduce heteroscedasticity (Sokal et al. 1981). Duncan's Multiple Range Tests (DMRT) were performed to get homogeneous sub-sets of micro-sites, slope treatments and rainwater harvesting treatments at $p < 0.05$ level. To obtain the relations between soil water content, soil nutrient and vegetation diversity and productivity, the Pearson correlation coefficients were calculated. The least significant difference test was used to compare treatments at the $p < 0.05$ levels. Regression equations were also developed to find out the relationship between herbage diversity variables and soil resources/herbage biomass.

Results

Soil nutrients

In June 2005, gravel fraction was highest ($p < 0.05$) in >20% slope and lowest in 10%–20% slope area. Sand content was highest in 10%–20% slope ranging from 7.5% to 17.3%. Combined concentration of silt and clay fraction in soil did not vary within the slopes but sand fraction was highest (16.07%) in 10%–20% slope (Table 1). Soil was acidic in reaction (pH = 6.88), whereas the average concentrations of SOC, ammonical nitrogen (NH_4-N), nitrate nitrogen (NO_3-N) and phosphate phosphorus (PO_4-P) were 0.760%, 22.15 mg·kg^{-1}, 2.50 mg·kg^{-1} and 4.51 mg·kg^{-1}, respectively. Soil pH, EC and available NH_4-N differed ($p > 0.05$) neither due to slope nor due to RWH treatment, but SOC and NO_3-N and PO_4-P availability varied ($p < 0.05$) with slope gradient only. All soil variables were highest in <10% slope. Respective values of soil pH, EC, SOC, NH_4-N, NO_3-N and PO_4-P were 5.0%, 5.3%, 25.0%, 19.1%, 14.2% and 105.1% (gradient) in <10% slope, which are greater than those in >20% slope. Above-mentioned gradients were reduced to −1.0%, −20.8%, 16.0%, 0, −7.0% and −15.0% for the respective soil variables (i.e., increase in these value in >20% slope). Soil pH ($p < 0.05$), EC, NH_4-N, NO_3-N and PO_4-P were highest in >20% slope. The values of pH, EC, NH_4-N, NO_3-N and SOC were lowest in 10%–20% slope, whereas EC and PO_4-P were lowest in <10% slope. In RWH treatments, highest SOC, NH_4-N and PO_4-P were in CT plots, NO_3-N in Gradonie plots and pH and EC in VD plots. Concentrations of NH_4-N, NO_3-N and EC were lowest in the control plots, whereas pH, SOC and PO_4-P were lowest in CT, Gradonie and BT plots, respectively. The interactions of Slope × RWH treatment were not significant for all soil variables. Considering the changes in soil variables between 2005 and 2008, paired t-test indicated an increase in soil pH, EC, NO_3-N and PO_4-P and a decrease in NH_4-N and SOC concentrations in June 2008, compared to the soil variables in June 2005, but the increase/decrease was significant ($p < 0.05$) only for pH, NH_4-N, NO_3-N and PO_4-P.

Table 1. Soil physico-chemical properties and nutrients status influenced by natural slopes and rainwater harvesting treatments in Aravalli hills

Slope	RWH treatment	pH		EC (mS·m^{-1})		SOC (%)		NH_4-N (mg·kg^{-1})		NO_3-N (mg·kg^{-1})		PO_4-P(mg·kg^{-1})	
		2005	2008	2005	2008	2005	2008	2005	2008	2005	2008	2005	2008
<10%	Control	6.78±0.24	7.15±0.08	0.15±0.03	0.18±0.03	0.98±0.10	0.92±0.11	27.47±2.18	13.16±2.11	2.85±0.27	2.72±0.54	7.73±0.25	11.96±1.71
	Contour trench	6.79±0.31	6.75±0.05	0.25±0.14	0.21±0.02	0.78±0.14	0.92±0.15	20.31±1.67	14.82±2.80	2.40±0.36	4.70±1.17	5.07±0.52	14.94±1.99
	Gradonie	7.02±0.28	6.89±0.05	0.14±0.02	0.15±0.03	0.98±0.16	0.72±0.16	23.99±3.11	14.76±0.94	2.83±0.25	5.40±0.93	6.42±1.56	18.16±2.34
	Box trench	7.00±0.15	6.89±0.12	0.28±0.09	0.18±0.02	0.92±0.10	0.62±0.12	24.39±2.75	15.46±1.99	2.97±0.23	5.40±1.05	6.06±1.05	13.13±1.45
	V-ditch	6.91±0.08	6.91±0.08	0.18±0.04	0.24±0.05	0.88±0.06	0.86±0.08	25.08±3.28	16.26±2.87	2.81±0.37	4.28±0.85	4.93±0.72	14.66±1.02
10%–20%	Control	6.64±0.16	6.80±0.06	0.13±0.02	0.14±0.02	0.58±0.05	0.50±0.16	23.42±3.48	13.63±1.68	2.44±0.26	2.96±0.49	3.70±0.50	16.96±3.46
	Contour trench	6.80±0.28	6.80±0.11	0.13±0.02	0.18±0.02	0.49±0.07	0.68±0.18	18.94±1.64	15.59±3.68	2.16±0.20	3.32±0.48	5.27±1.21	16.32±2.53
	Gradonie	6.67±0.24	6.75±0.08	0.15±0.02	0.21±0.04	0.68±0.11	0.64±0.10	20.05±1.72	12.67±1.12	2.27±0.15	2.97±0.70	5.36±0.76	17.25±1.49
	Box trench	6.52±0.24	6.71±0.17	0.14±0.02	0.22±0.03	0.69±0.10	0.72±0.05	20.91±2.38	12.07±3.11	2.13±0.05	4.44±0.96	4.31±0.23	14.27±2.03
	V-ditch	6.35±0.25	7.14±0.20	0.31±0.10	0.23±0.04	0.83±0.13	0.87±0.10	25.91±2.87	13.85±1.69	2.39±0.12	4.45±0.49	4.01±0.45	14.91±2.26
>20%	Control	6.66±0.15	7.02±0.05	0.15±0.02	0.22±0.02	0.69±0.13	0.75±0.19	19.13±2.44	14.15±2.40	2.50±0.26	5.49±0.92	2.40±0.30	16.58±1.06
	Contour trench	6.57±0.25	6.88±0.11	0.21±0.04	0.26±0.03	0.86±0.12	0.76±0.13	25.66±3.00	17.08±2.29	2.64±0.13	4.23±0.75	2.31±0.25	20.56±3.09
	Gradonie	6.92±0.10	6.93±0.14	0.27±0.07	0.21±0.04	0.62±0.15	0.67±0.10	22.07±3.21	13.82±1.49	2.45±0.23	6.37±2.31	2.62±0.48	15.97±2.12
	Box trench	6.68±0.23	7.03±0.03	0.17±0.04	0.23±0.03	0.85±0.16	0.71±0.07	17.50±1.53	15.13±3.92	2.41±0.29	3.93±0.60	4.29±0.68	15.30±1.12
	V-ditch	6.75±0.06	7.12±0.08	0.13±0.03	0.26±0.02	0.59±0.17	0.59±0.09	17.33±1.57	14.50±1.84	2.17±0.16	4.20±0.35	3.10±0.64	17.29±1.55
Two-way ANOVA													
F-value													
Slope		2.532	2.774	0.369	3.478	5.568	1.530	3.001	0.521	5.712	2.156	21.898	1.929
RWH treatment		0.421	2.988	0.634	1.997	0.325	0.480	0.413	0.419	0.276	0.687	0.776	1.189
Slope × RWH treatment		0.438	1.269	1.810	0.769	1.142	1.042	1.878	0.200	0.709	1.231	1.909	0.734
P-value													
Slope		0.088NS	0.070NS	0.693NS	0.037*	0.006**	0.225NS	0.057NS	0.597NS	0.005**	0.125NS	0.000**	0.154NS
RWH treatment		0.793NS	0.026*	0.640NS	0.106NS	0.860NS	0.749NS	0.799NS	0.794NS	0.893NS	0.604NS	0.545NS	0.325NS
Slope × RWH treatment		0.893NS	0.277NS	0.093NS	0.632NS	0.349NS	0.416NS	0.080NS	0.200NS	0.683NS	0.297NS	0.075NS	0.661NS

Notes: Significant at *$p < 0.05$, **$p < 0.01$, NS- not-significant. mS·m^{-1} is milli Seimens per meter. Values are mean of five replications with ±SE.

Soil water dynamics

Average soil water content (SWC) for a month ranged from 3.67% in December to 15.76% in September. The interaction between month and slope was significant ($p < 0.05$), but average SWC of all observations was in RWH treated plots (average of the plots of CT, gradonie, BT and VD treatments) was 7.6% greater than that in the control plots (Table 2). Soil water content also varied ($p < 0.05$) between microsites in all three observations i.e., July, September and December 2008 (Fig. 1b-c). Soil water content had a difference ($p < 0.05$) i.e., 7.6% and 4.7% in July, 5.3% and 9.1% in September, and 33.0% and 15.9% in December at MSP and LSP, respectively, as compared to SWC at USP microsite. In July and December 2008, SWC was highest at MSP and lowest at USP, but it followed an increasing trend from USP to LSP in September 2008 (Fig. 1d). Among the slope treatments, SWC was highest ($p < 0.05$) in <10% slope and lowest in 10-20% slope in all observations. Average SWC was 22.5% and 15.5% lesser in 10%–20% slope ($p < 0.05$) and >20% slope respectively, than the SWC in <10% slope. However, the gradient in SWC between <10% slope to >20% slope was 20.9% in July, 16.7% in September and 39.5% in December. We did not find significant ($p > 0.05$) differences in SWC among RWH treatments, but SWC was lowest in the control plots in all observations. The highest SWC was in Gradonie plots in July and September and in BT plots in December 2008. Average increases in SWC (three observations) were 9.4%, 12.0%, 4.2% and 5.0% in CT, Gradonie, BT and VD plots respectively, as compared to the SWC in control plots. The decrease in soil water due to utilization by the growing vegetation from September to December was highest at USP and lowest at MSP microsites. Among the slopes, the depletion was 75.8% in >20% slope, 83.2% ($p < 0.05$) in 10%–20% and 71.7% in <10% slope. Soil water depletion was highest in VD plots (78.0%) and lowest in BT plots.

Vegetation diversity (VD)

Species richness (R), diversity (H'), dominance (D) and evenness (e) did not vary ($p > 0.05$) among micro-sites (Table 3). Further, interactions of micro-site × slope and micro-site × RWH treatments were not significant ($p > 0.05$). However, species richness (by 2.7%) and diversity (by 2.9%) were highest at LSP, whereas evenness was highest at MSP among the microsites. Dominance had a decreasing trend from USP to LSP of microsites. Among the slopes, species richness (by 12.5%), diversity (17.4%) and evenness (7.2%) were greater ($p < 0.05$) in <10% slope than those in the other slopes (>20% slope). Species richness showed lowest in 10%–20% slope. Dominance had highest value in >20% slope. Considering RWH treatments, diversity and evenness were lowest, whereas dominance was highest in the control plots. The plots with VD treatment showed highest species richness and evenness but lowest dominance. The highest value of diversity was in the CT plots. All variables showed not significant interactions ($p > 0.05$) between slope and RWH treatment.

Table 2. Average soil water content (%, w/w) in July, September and December 2008 influenced by natural slope gradient and rainwater harvesting treatments in Aravalli hills

Slope	RWH treatment	July	September	December	Soil water depletion [a]
<10%	Control	14.18±0.85	17.18±1.68	4.81±0.85	70.34±3.34
	Contour trench	10.48±0.87	16.72±2.37	4.57±0.96	72.99±4.30
	Gradonie	10.87±2.00	18.93±2.07	415±0.82	77.53±3.69
	Box trench	12.75±1.73	17.76±1.22	5.56±0.36	68.43±0.63
	V-ditch	13.21±0.93	19.05±1.25	5.69±0.33	69.15±2.52
10%–20%	Control	8.96±1.21	13.45±3.22	1.97±0.67	87.02±2.20
	Contour trench	12.76±1.86	16.20±1.31	3.13±0.44	79.30±2.58
	Gradonie	12.43±2.41	15.17±1.65	2.91±0.49	81.01±2.09
	Box trench	8.82±0.80	13.51±1.20	2.36±0.32	81.96±2.95
	V-ditch	11.04±1.62	11.66±1.41	1.58±0.37	86.73±2.58
>20%	Control	9.49±1.57	12.59±1.70	3.50±0.99	74.56±6.57
	Contour trench	9.91±1.26	16.47±1.58	3.35±0.40	78.92±1.44
	Gradonie	11.87±0.95	16.65±2.57	4.14±0.56	73.57±3.93
	Box trench	10.23±1.22	15.27±1.87	3.88±0.71	73.85±4.38
	V-ditch	9.35±1.26	15.80±1.40	3.40±0.30	78.13±1.88

Repeated measure ANOVA				Two way ANOVA
Tests of within-subjects effects	*df*	MS	*F*-value	*F*-value
Microsite	2	2790.205	516.4**	-
Microsite × slope	4	13.205	2.444*	-
Microsite × RWH treatment	8	4.023	0.745NS	-
Tests of between-subjects effects				
Slope	2	144.297	7.759**	0.000**
RWH treatment	4	9.359	0.503NS	0.798NS
Slope × RWH treatment	8	17.410	0.936NS	0308NS

Notes: Significant at $*p < 0.05$, $**p < 0.01$, NS- not-significant. Values are mean ±SE of five replicate plots. "a" shows that soil water depletion is from Sept. to Dec. 2008.

Photo-synthetically active radiations

Photo-synthetically active radiations in September 2008 ranged from 1006.0 to 1807.0 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Though average PAR interception (PARint) did not vary due to vegetation among the microsites, PARint ranged between 24.5% at LSP and 27.2% at USP microsite. Among the slopes, average (pooled data of microsites and RWH treatments) PARint ranged from 25.9% in <10% slope to 26.5% in >20% slope (Table 4). Average PARint for RWH treatments was lowest ($p = 0.054$) in the control at USP and MSP micro-sites and in Gradonie treatment at LSP. The PARint was most ($p < 0.05$) in CT treatment at USP and LSP and in VD treatment at MSP micro-site. There was a linear decrease in PARint from USP to LSP in 10%–20% and >20% slopes.

Vegetation height and biomass

Vegetation height increased with slope gradient from LSP to USP in a plot. However, Duncan's Multiple Range Tests (DMRT) indicated (pooled data of slopes and RWH treatments for mi-

crosites) that tallest ($p < 0.05$) vegetations (64.1 cm high) were at MSP (60.9 cm), followed by LSP in >20% slope, whereas shortest vegetation was 38.5 cm in height at USP in 10%–20% slope (Table 4). Vegetation height varied ($p > 0.05$) due to slope. The vegetation height in 10%–20% slope was 7.5% lower, whereas vegetation height in >20% slope was 34.7% taller than the vegetation height in <10% slope. Vegetation height showed an increasing trend of LSP<MSP<USP in the plots of CT, Gradonie and VD treatments but it was in the order of USP<MSP<LSP in the control plots. Vegetation height was greater at MSP and USP in the plots of VD treatment and at LSP in the plots of CT treatment.

Green and dry biomasses were lowest ($p < 0.01$) at USP. Average of these biomasses (irrespective of slope and RWH treatments) was increased to 1.52-fold and 1.56-fold, respectively at LSP and at USP. All interactions with microsites were not-significant ($p > 0.05$). But the dry biomass (USP to LSP) was increased to 2.13-fold, 1.65-fold and 1.97-fold in <10%, 10%–20% and >20% slope, respectively. The highest biomass was in 10%–20% slopes, whereas the lowest biomass was in <10% slope (Table 5). The increases in green and dry biomasses were 10.0% and 9.0% in 10%–20% slope, and 6.0% and 5.0% in >20% slope, which are more than those in <10% slope. Interactions between microsites and slopes for RWH treatments, the biomasses were lowest ($p < 0.05$) in the control plots. The highest ($p < 0.05$) green and dry biomasses were in CT plots, which were 1.25- and 1.27-fold more than those in the control plots. The effect of RWH treatment was highest in CT plots, because of minimization in the differences of the dry biomass between USP and LSP microsites in a plot. The interaction of slope with RWH treatment indicated that the highest dry biomass was in CT plots in all slope.

Correlations and regressions

Existing hillslope gradient had positive relation ($p < 0.05$) with soil available NH_4-N and negative relations with NO_3-N and PO_4-P, but did not show any relation with soil pH, EC and SOC in June 2005. In June 2008, EC, NO_3-N, soil water depletion and vegetation height showed a positive relation with existing hillslope gradient, whereas sand content, PAR reduction and SWC in July and Septembers showed a negative relation with slope gradient (Table 5). Gravel content positively related with SWC at USP ($r = 0.237$, $p < 0.05$) and MSP ($r = 0.260$, $p < 0.05$) in December 2008. All observations of SWC had positive relations with vegetation height, species richness at MSP and species evenness. Soil pH and EC had positive relations with vegetation height, but soil pH was negatively related with species diversity and dominance at USP. Vegetation height had positive relations with NH_4-N and NO_3-N. Available NH_4-N was positively related with dry herbage biomass, which was positively related with vegetation height, PAR reduction and gravel percent at LSP, but showed negative relation with species richness at MSP.

Regression analysis showed significant exponential relation of species dominance with vegetation height ($R^2 = 0.0894$ at USP to 0.150 at MSP, $F_{1,73} = 7.17$ to 10.94, $p < 0.01$), but species evenness was inversely related with SWC in September ($R^2 = 0.056$ at LSP to 0.145 at USP, $F_{1,73} = 4.48$ to 11.11, $p < 0.05$) and cubic relation ($R^2=0.147$, $F_{3,71} = 4.10$, $p < 0.01$) with NH_4-N availability in June (Fig. 2). Species diversity had quadratic relation ($R^2=0.100$, $F_{2,72}=3.99$, $p < 0.05$) with SWC in July (at MSP) and sigmoidal relation ($R^2=0.065$, $F_{1,73} = 5.08$, $p < 0.05$) with PO_4-P in June. Average dry herbage indicated log relation ($R^2=0.057$, $F_{1,73} = 4.43$, $p < 0.05$) with vegetation height at MSP and cubic relation ($R^2=0.210$, $F_{3,73} = 6.27$, $p < 0.001$) at LSP. Dry biomass showed a quadratic relation with NH_4-N ($R^2=0.086$, $F_{2,72} = 3.37$, $p < 0.05$) and vegetation diversity ($R^2=0.086$, $F_{2,72} = 3.40$, $p <$ 0.05), (Fig. 3).

Discussion

Water-nutrient gradients have been found to be the most important environmental gradients determining the distribution and composition of plant communities in hillslopes. Since water flows towards down slope area, manipulation of hillslopes with RWH structure influenced plant community organization and vegetation growth, because of variations in water, light, and soil nutrients (Hwang et al. 2009). The variation in PAR interception (PARint) among the microsites/slope treatments in present study seemed to be due to a combined effect of vegetation height and population ($r = 0.340$, $p < 0.01$), as correlation between PARint and vegetation height/ species evenness at USP was negative (Table 6). This suggests that a population with unevenly distributed species has capacity of higher interception producing higher biomass ($r = 0.262$, $p < 0.05$ at LSP). PAR interception by the maize plants cultivated under conventional tillage was 30% higher than that in the maize plants cultivated under no-tillage system (Bergamaschi et al. 2010).

Changes in soil resources

Soil properties and topographic features are the two general physiographic factors controlling soil water and nutrients availability on hillslopes. The combined effects of these two factors influenced soil pH and EC negatively and SOC and nutrients positively between >20% and <10% slopes in June 2005. Frankenberger et al. (1999) explained that once the soil profile is saturated, soluble nutrients are more easily transported to foothills areas, with water flowing laterally as subsurface flow. But highest availability of soil water (July, September et al. 2008), NH_4-N and NO_3-N in June 2008 at MSP suggests that the improvement in the soil variable in upslope area is due to rainwater harvesting. A reduction in the differences in soil variables between USP and LSP in June 2008 suggests that soil conditions are improved further due to rainwater harvesting. However, a negative relation between SWCs in July/September and slope gradient suggested that an increase in SWC is toward down slope area. Frankenberger et al. (1999) observed that soil moisture at the top of a hill was about 35% less than soil moisture at the bottom.

Though changes in quantity and intensity of rainfall during June to September influenced SWC, but a positive relation of

SWC (July, September and December) with species richness (r = 0.228 to 0.393, $p < 0.01$ at MSP) and species evenness (r = 0.268 to 0.424) suggested that these vegetations improved soil water probably by reducing run-off and promoting infiltration during rainfall. Interestingly, increase in the difference in SWCs between USP and MSP in September indicated that soil texture is more important in controlling hillslope soil water during wet periods i.e., in September, while topographic features (slope gradient) showed more control on soil water in hillslope during drier period. This finding was similar to the observations (Yeakley et al. 1998). Differences in soil water, SOM, total N, available N, P, K and the soil particle fractions of size <0.002 mm between different slope segments were also observed in other studies (Ge et al. 2007). The lowest SWC, soil pH, SOC, NH_4-N and NO_3-N in 10%–20% slope area were due to highest sand content and losses of run-off water from this slope. But increased concentrations of EC, NH_4-N, NO_3-N and PO_4-P in >20% slope were due to disintegration of rock fragments, mineralization of SOC and decomposition of the litters of growing vegetation influenced by RWH. By way of conserving soil and water, RWH treatments improved soil water and nutrients status. The highest ($p < 0.05$) SWC in Gradonie particularly in July and September (even at USP) suggested that this technique is beneficial in improving SWC towards upslope area particularly when rainfall is high and regular in nature. But greater concentration of SOC and PO_4-P in CT plots might be due to harvesting of greater amount of rainwater and its storage into deeper soil profiles, which facilitated mineralization and availability for their use in herbage growth and biomass.

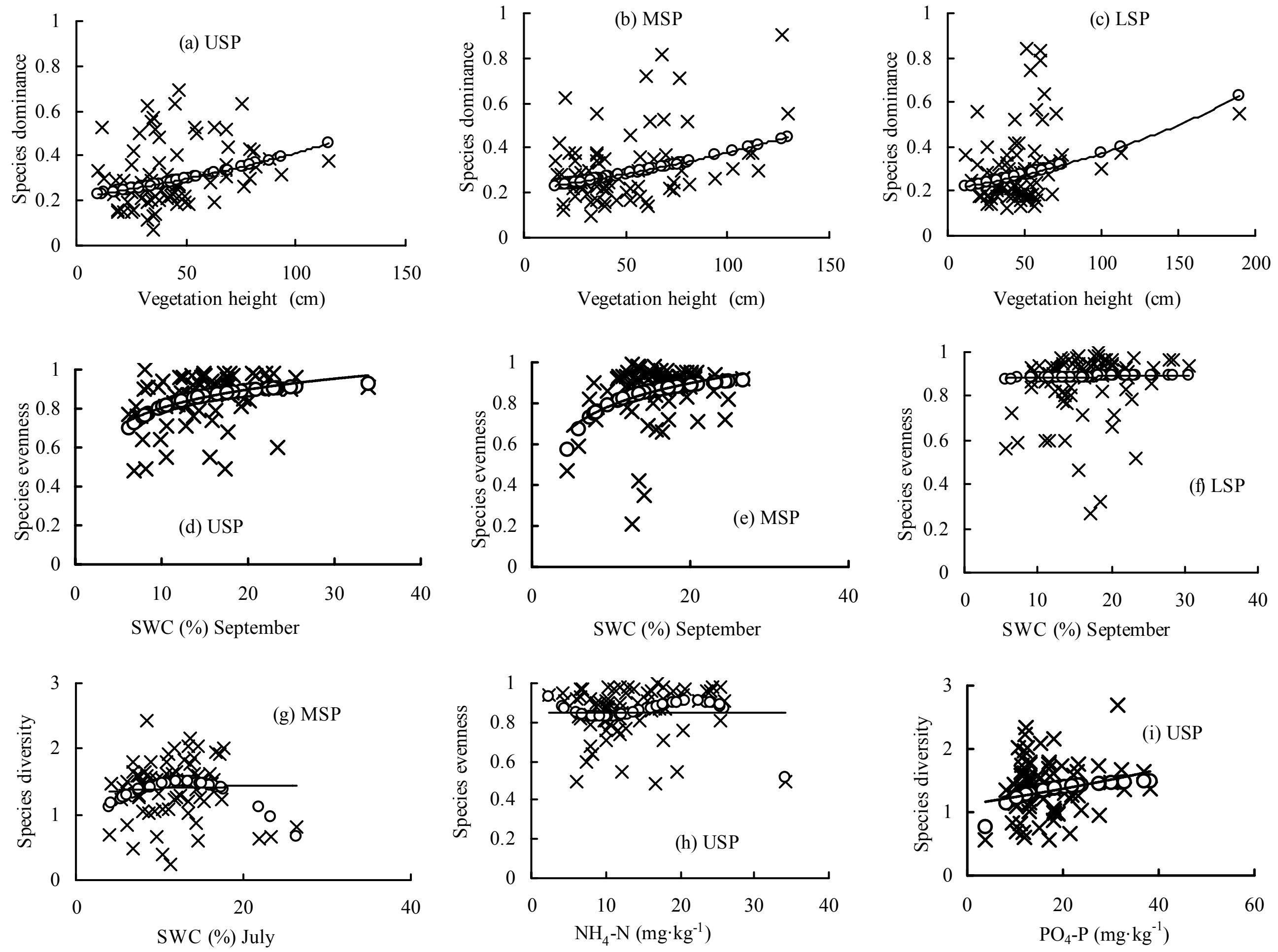

Fig. 2 Regression relations of vegetation height and soil resources with diversity variables of herbage in 2008 at upper (USP), middle (MSP) and lower (LSP) sampling position (micro-sites) within a plot. Symbol (X) represents the observed value and, symbol (O) represents the estimated values of diversity variables. Linear trend has been shown by a solid line.

Species diversity and biomass

The effect of soil fertility on plant primary production, community structure, and diversity was demonstrated in many plant communities particularly in fertilization experiments (Chapin et al. 1985; Fox 1992). But SWC at MSP/LSP increased 4.7% to 33.0% more than that at USP under RWH, which promoted species richness and species diversity. Therefore, herbage biomass was increased by 1.52- to 1.56-fold. There was a positive corre-

lation between SWC and species richness (at MSP) and evenness. Chipman et al. (2002) also observed that there were higher richness, narrower species tolerance, and more overlap of species frequencies in upland vascular plant species in the lower parts of hillslopes, whereas the upper parts of hillslopes had lower richness in mixedwood boreal forest of Saskatchewan, Canada. SWC and PO_4-P availability was in favour of dominance, resulting in an increasing trend in species dominance towards upslope areas i.e., USP and evenness at MSP. A trend of increase in the vegetation height ($R^2 = 0.089$, $p < 0.01$) with slope was positively related with species dominance. But relatively greater vegetation height at MSP particularly in >20% slope was due to the enhanced ($p < 0.05$) soil water, NH_4-N and NO_3-N availability under rainwater harvesting as described in earlier research (Tilman 1999), where application of fertilizer enhanced productivity and simultaneously decreased vegetation diversity. The highest species diversity and herbage biomass in CT plots were probably due to SOC and PO_4-P availability and greater storage of run-off water that facilitated vegetation growth too. The increase of soil water in this treatment flowed downward to increase SWC at LSP, which promoted vegetation growth and biomass (Rastetter et al. 2004).

Greater average biomass in 10%–20% and >20% slopes was due to increase in SWC and nutrients in higher slopes (former two slopes), which decreased differences in the values of soil variables (pH, EC and soil nutrients) between <10% slope and >20% slope in 2008, as compared to the differences in 2005. The enhanced biomasses in 10%–20% slope was also due to greater soil water usage (83.2% water usage) as compared to the other slopes, but regular rain during growth period of July to September might have also facilitated growth and biomass of plants in this slope. However, biomasses in >20% slope was increased due to the combined effects of regular rainfall and soil water usage (75.8%), compared to <10% slope (Svoray et al. 2004; Danalatos et al. 2007). Despite of relatively greater species richness, species evenness, vegetation height and NH_4-N availability, lesser herbage biomass in the plots of VD treatment was probably due to low soil water (i.e., low SWC) and few vegetation population. But the effect of CT treatments in minimizing difference in herbage biomass between USP and LSP was greater (i.e., 1.67-fold in CT plots as compared to 2.19-fold in the control plots) than that of other RWH treatments. The increases in herbage growth and biomass was due to increasing species diversity, which increased with soil nutrients i.e., NH_4-N (Fridley 2002). Positive relations of species diversity with SWC ($R^2 = 0.144$, $F_{2,72} = 3.99$, $p = 0.011$) and available PO_4-P ($R^2 = 0.065$, $F_{1,72} = 5.08$, $p = 0.05$) were in favour of vegetation diversity (Foster et al. 2004; Bradley et al. 2006). The positive and negative relations of vegetation diversity and species richness ($r = -0.244$, $p = 0.035$, n=75) with biomass indicated that the increase in herbage biomass was the effects of species composition rather than species richness (Mudler et al. 2001). This might be due to dominance of *Themada quadrivalvis* (a tall grass in higher slope area), which played an important role in enhancing herbage biomass.

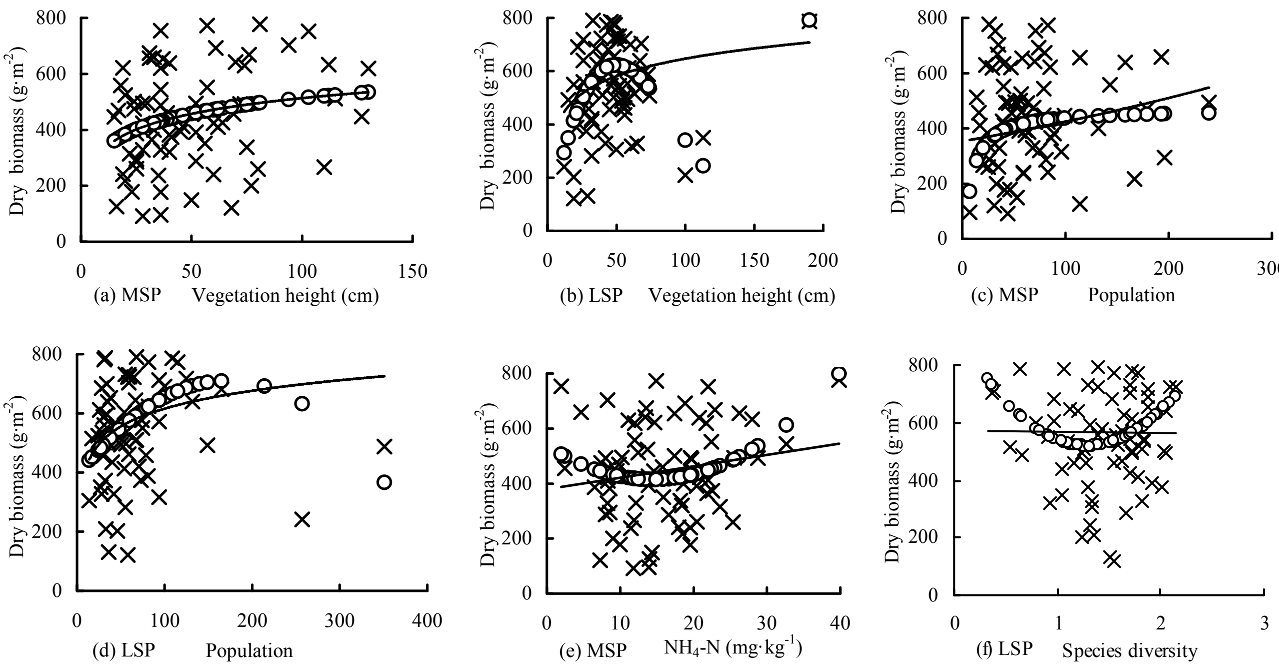

Fig. 3 Regression relations of vegetation parameter, soil resources and herbage diversity with herbage productivity in 2008 at middle (MSP) and lower (LSP) micro-sites in a plot. Symbol (*X*) represents the observed value. Symbol (*O*) represents the estimated values of diversity variables. Linear trend has been shown by a solid line.

Table 3. Species richness index (*R*) and species diversity index (*H*) influenced by natural slope, rainwater harvesting treatments and microsites within plots in Aravalli hills

Slope	RWH treatment	Species richness			Species diversity			Species dominance			Species evenness		
		USP	MSP	LSP	USP	MSP	LSP	USP	MSP	LSP	USP	MSP	LSP
<10%	Control	0.78±0.18	0.66±0.10	0.89±0.14	1.33±0.26	1.29±0.16	1.53±0.16	035±0.08	0.32±0.05	0.28±0.05	0.85±0.03	0.86±0.03	0.87±0.07
	C. trench	0.76±0.12	0.89±0.08	0.93±0.08	1.58±0.23	1.77±0.14	1.81±0.14	0.27±0.07	0.22±0.04	0.19±0.02	0.86±0.07	0.87±0.05	0.92±0.02
	Gradonie	0.88±0.09	0.89±0.06	0.92±0.10	1.68±0.27	1.75±0.15	1.71±0.14	0.24±0.05	0.22±0.05	0.21±0.03	0.90±0.03	0.86±0.05	0.93±0.03
	Box trench	0.74±0.08	0.76±0.15	0.74±0.10	1.54±0.23	1.27±0.27	1.37±0.23	0.25±0.07	0.38±0.10	0.32±0.08	0.96±0.01	0.84±0.06	0.91±0.03
	V-ditch	0.73±0.17	0.85±0.09	0.72±0.07	1.37±0.27	1.76±0.10	1.55±0.11	0.31±0.07	0.19±0.02	0.24±0.03	0.92±0.02	0.93±0.01	0.92±0.03
10%–20%	Control	0.66±0.09	0.68±0.10	0.67±0.16	1.52±0.17	1.37±0.05	1.22±0.28	0.28±0.06	0.31±0.03	0.43±0.12	0.82±0.05	0.82±0.06	0.69±0.10
	Control trench	0.76±0.03	0.69±0.07	0.63±0.14	1.58±0.15	1.39±0.19	1.13±0.35	0.25±0.04	0.29±0.06	0.47±0.15	0.88±0.03	0.91±0.15	0.69±0.13
	Gradonie	0.70±0.04	0.67±0.09	0.71±0.05	1.38±0.11	1.44±0.22	148±0.19	0.29±0.03	0.30±0.07	0.29±0.07	0.86±0.02	0.88±0.03	0.85±0.05
	Box trench	0.52±0.05	0.57±0.05	0.65±0.12	1.12±0.17	1.23±0.25	1.46±0.19	0.40±0.07	0.38±0.10	0.29±0.07	0.79±0.06	0.83±0.10	0.86±0.68
	V-ditch	0.70±0.03	0.67±0.12	0.78±0.12	1.32±0.09	1.37±0.11	1.52±0.15	0.33±0.05	0.28±0.03	0.26±0.04	0.79±0.08	0.90±0.03	0.90±0.02
>20%	Control	0.60±0.09	0.55±0.10	0.93±0.11	1.03±0.14	1.06±0.14	1.60±0.15	0.45±0.08	0.41±0.07	0.25±0.04	0.78±0.11	0.85±0.10	0.83±0.06
	Control trench	0.73±0.09	0.63±0.07	0.67±0.14	1.25±0.19	1.31±0.12	1.35±0.22	0.37±0.07	0.30±0.03	0.32±0.07	0.80±0.02	0.91±0.03	0.89±0.03
	Gradonie	0.73±0.13	0.68±0.10	0.71±0.07	1.41±0.13	1.12±0.23	1.18±0.14	0.31±0.06	0.44±0.12	0.39±0.09	0.79±0.10	0.67±0.12	0.77±0.11
	Box trench	0.86±0.06	0.78±0.12	0.54±0.06	1.73±0.20	1.52±0.33	1.19±0.15	0.22±0.06	0.31±0.03	0.38±0.06	0.91±0.04	0.79±0.11	0.81±0.08
	V-ditch	0.72±0.13	0.84±0.10	0.81±0.11	1.15±0.15	1.32±0.13	1.50±0.06	0.37±0.06	0.31±0.02	0.26±0.04	0.85±0.08	0.87±0.04	0.93±0.03
Repeated measure ANOVA													
Tests of within-subjects effects	*df*	MS	*F*-value	*df*	MS	*F*-value	*df*	MS	*F*-value		*df*	MS	*F*-value
Microsite	2	0.02268	0.564NS	2	0.04148	0.334NS		0.001795	0.106NS		2	0.000360	0.028NS
Micrositexslope	4	0.00822	0.205NS	4	0.03992	0.322NS		0.013000	0.765NS		4	0.02037	1.575NS
Micrositexrwh treatment	8	0.4517	1.124NS	8	0.124	0.999NS		0.018500	1.090NS		8	0.01747	1.351NS
Repeated Measure ANOVA													
Tests of between-subjects effects	*df*	MS	*F*-value	*df*	MS	*F*-value	*df*	MS	*F*-value		*df*	MS	*F*-value
Slope	2	0.370	4.839*	2	1.164	3.869*	2	0.117	3.118*		2	0.09595	2.805NS
RWH treatment	4	0.05208	0.681NS	4	0.147	0.488NS	4	0.02664	0.709NS		4	0.03263	0.954NS
Slope×RWH treatment	8	0.04383	0.573NS	8	0.774	0.627	8	0.01938	0.516NS		8	0.02007	0.587NS

Notes: Significant at *$p < 0.05$, **$p < 0.01$, NS- not-significant. Values are mean of five replications with ±SE.

Table 4. Photosynthetically active radiations (PAR) interception (%) and vegetation height influenced by natural slope, rainwater harvesting treatments and microsites within plots in Aravalli hills

Slope	RWH treatment	PAR interception (%)			Vegetation height (cm)		
		USP	MSP	LSP	USP	MSP	LSP
<10%	Control	16.60±2.96	22.80±6.28	31.40±4.23	42.0±9.96	48.8±7.12	39.6±6.50
	Control trench	33.80±10.63	21.40±1.97	38.00±8.89	46.6±7.79	47.0±9.47	41.6±6.27
	Gradonie	24.80±6.18	23.80±5.29	23.60±1.75	43.0±6.80	35.6±5.99	38.0±5.89
	Box trench	14.20±2.06	25.20±5.58	26.80±6.21	34.4±8.23	47.2±8.98	48.0±6.06
	V-ditch	20.60±3.56	41.40±10.09	24.00±4.27	52.0±6.78	41.8±8.33	39.8±6.58
10%–20%	Control	23.00±3.36	18.40±2.54	20.60±2.40	23.4±4.20	29.8±7.24	34.4±10.38
	Control trench	31.20±4.41	33.40±2.12	32.40±3.39	40.8±11.03	35.60±8.74	49.0±4.11
	Gradonie	24.00±2.39	24.40±5.99	16.20±1.91	51.4±16.33	49.8±20.35	45.4±8.13
	Box trench	28.80±3.64	28.00±3.08	20.40±2.16	39.4±4.83	43.6±7.61	41.0±6.77
	V-ditch	34.60±7.30	29.20±3.94	24.80±1.28	37.4±7.93	36.8±9.56	38.8±3.57
>20%	Control	30.40±3.91	23.60±1.91	23.60±2.98	51.2±9.58	68.2±12.67	48.8±10.59
	Control trench	30.20±2.13	27.80±5.34	25.20±1.11	48.4±12.63	54.0±14.61	73.6±29.29
	Gradonie	31.40±4.43	23.60±3.22	16.40±2.44	37.4±8.78	57.6±19.89	58.0±12.29
	Box trench	33.40±8.85	32.80±8.33	21.20±3.37	46.4±6.68	52.4±10.08	57.6±4.73
	V-ditch	31.40±6.72	24.20±0.97	22.60±0.93	61.0±11.30	88.4±12.96	66.4±12.71
Repeated measure ANOVA							
Tests of within-subjects effects		*df*	MS	*F*-value		MS	*F*-value
Microsite		2	157.99	1.84NS		625.39	2.407NS
Microsite × slope		4	456.77	5.31**		557.35	2.145NS
Microsite × treatment		8	148.32	1.72NS		217.75	0.838NS
Tests of between-subjects effects							
Slope		2	8.88	0.051NS		7040.02	5.929**
Treatment		4	435.05	2.48*		460.53	0.388NS
Slope × treatment		8	110.75	0.63NS		729.19	0.614NS

Notes: Significant at *$p < 0.05$, **$p < 0.01$, NS- not-significant. MS represents mean square. Values are mean of five replications with ±SE.

Table 5. Green and dry biomasses of herbaceous vegetation influenced by natural slope, rainwater harvesting treatments and microsites within a plot in Aravalli hills

Slope	RWH treatment	Green herbage (g m^{-2})			Dry herbage (g m^{-2})		
		USP	MSP	LSP	USP	MSP	LSP
<10%	Control	635.2±164.77	787.2±148.48	1258.2±186.56	295.6±90.18	326.6±54.56	596.2±86.86
	Control trench	922.4±157.18	1083.4±162.50	1293.8±249.26	419.0±78.58	487.6±83.20	624.8±126.44
	Gradonie	800.2±202.41	897.8±110.02	1181.4±234.70	393.0±98.57	425.2±55.47	572.0±112.29
	Box trench	534.4±127.46	865.4±231.33	1166.6±24.41	263.6±70.60	436.2±124.33	538.6±22.43
	V-ditch	809.6±130.39	729.6±141.36	1050.6±224.78	369.6±60.32	328.2±63.93	511.2±115.63
10%–20%	Control	826.0±221.37	693.6±131.83	1238.8±172.69	396.4±100.85	327.8±88.94	584.2±97.49
	Control trench	890.6±63.83	934.0±177.24	1475.20±118.09	401.4±29.08	400.8±81.97	738.8±46.31
	Gradonie	873.2±162.14	1157.0±117.46	1281.0±123.49	410.0±89.98	533.2±61.12	633.6±52.30
	Box trench	737.4±74.82	1196.0±191.59	1237.8±175.47	318.8±24.79	562.6±84.02	596.6±87.39
	V-ditch	997.0±223.05	906.6±143.01	953.2±219.51	454.6±108.82	435.0±68.94	383.2±89.68
>20%	Control	591.8±131.32	888.6±260.14	1070.4±141.99	274.6±68.24	404.4±110.31	515.8±53.21
	Control trench	893.2±151.58	1137.2±88.03	1390.0±184.93	433.6±80.23	555.8±49.79	651.0±74.14
	Gradonie	660.8±111.18	822.8±107.03	819.2±126.10	295.2±55.45	359.6±39.82	408.2±62.37
	Box trench	985.2±222.94	1147.6±239.87	1396.0±186.07	485.6±92.92	509.0±110.75	589.0±78.02
	V-ditch	545.8±126.38	1273.8±188.59	1212.6±147.20	255.2±61.66	571.2±92.15	573.0±71.25
Repeated measure ANOVA							
Tests of within-subjects effects		d*f*	MSE	*F*-value		MSE	*F*-value
Microsite		2	5342555.09	46.220**		787162.11	40.698**
Microsite × slope		4	102709.31	1.420NS		20162.26	1.042NS
Microsite × treatment		8	87131.22	1.205NS		24938.83	1.289NS
Tests of between-subjects effects							
Slope		2	160477.29	0.569NS		28969.12	0.502NS
Treatment		4	354033.13	1.255NS		84339.44	1.461NS
Slope × Treatment		8	192115.18	0.681NS		40907.58	0.709NS

Notes: Significant at *$p < 0.05$, **$p < 0.01$, NS- not-significant. Values are mean of five replications with ±SE.

Table 6. Correlations co-efficient (*r*) of different variables with herbage production influenced by natural slope and rainwater harvesting treatments in Aravalli hills (n=75).

Variables	Slope	Vegetation height	Green herbage	Dry herbage	PO_4-P	NH_4-N	Species richness	Species Diversity	Species dominance	Species evenness
Slope gradient	-	0.312**	NS	NS	NS	NS	NS	-0.318**	0.298**	-0.200(0.085)
Sand content	-0.451**	NS	NS	NS	NS	NS	NS	NS	NS	NS
Gravel	NS	NS	-0.261*(L)	-0.288*(L)	NS	NS	NS	NS	NS	NS
Soil pH	NS	0.299**	NS	NS	NS	NS	NS	-0.239*(U)	-0.264*(U)	NS
EC	0.289*	0.325**	NS	NS	NS	NS	NS	NS	NS	NS
SOC	NS	NS	NS	NS	NS	-0.236*	NS	NS	NS	0.252*(U)
NH_4-N	NS	0.228*(M)	0.230*	0.273*	NS	-	NS	NS	NS	NS
NO_3-N	0.284*(L)	0.251*(M)	NS	NS	NS	0.289*	NS	NS	NS	0.271*(M)
PO_4-P	NS	NS	NS	NS	-	NS	NS	NS	NS	NS
SWC July	-0.244*	0.333**	NS	NS	NS	NS	0.228*(M)	NS	NS	0.268*
SWC Sept.	-0.238*	0.355**	NS	NS	NS	NS	0.321**(M)	NS	NS	0.382**
SWC Dec.	NS	0.259**	NS	NS	NS	NS	0.393**(M)	NS	0.302**(U)	0.424**
SWC depletion	0.212(0.065)	NS	NS	NS	0.231*	NS	-0.281*(M)	-0.223*(M)	0.220(0.058)	-0.366**
PAR reduction	-0.244*(L)	-0.235*	0.262*(L)	0.250*(L)	NS	0.286**(L)	NS	NS	NS	-0.387*(U)
Vegetation height	0.471**	-	NS	0.236*(M)	NS	0.228*(M)	-0.249**(L)	-0.423**	0.302**	NS
Green herbage	NS	NS	-	0.978**	NS	0.230*	NS	0.247*(L)	NS	NS
Dry herbage	NS	0.236**(M)	0.994**	-	NS	0.273*	-0.285(M)	NS	NS	NS

Notes: Significant at ** $p < 0.01$, * $p < 0.05$, NS-not-significant. U, M and L are upper, middle and lower sampling position.

Conclusions and recommendations

Application of RWH techniques enhanced soil nutrients availability in higher slopes and reduced the variance in the values of soil variables between existing slopes i.e., >20% and <10% slopes in June 2005. Increased concentrations of NH_4-N, NO_3-N and PO_4-P in higher slopes promoted vegetation height and herbage biomass. Though an increasing trend of soil water content, species diversity and herbage biomass from USP to LSP microsites in a plot was observed, RWH techniques had positive role in enhancing SOC, pH, NH_4-N and NO_3-N values at MSP to promote species population, evenness and vegetation growth (height). Regular rainfall enhanced vegetation growth and its biomass in 10%–20% slope and >20% slope utilizing greater amount of soil water, resulting in a reduction in soil water in these slopes, compared to <10% slope. The highest diversity in CT treatment was related to herbage biomass and simultaneously greater availability of SOC and PO_4-P reinforced herbage growth and biomass production. Conclusively, soil texture and topographic features on hillslope controlled soil water and nutrients availability, but application of RWH techniques increased soil water storage. The nutrient retention minimized the effects of slope gradient to enhance vegetation composition and biomass production. Out of these four RWH treatments, CT was found to be the most suitable for increasing vegetation diversity and herbage biomass and minimizing yield (biomass) variance between the slopes. This practice may be applied in other areas to conserve soil resource and improve rangeland productivity in the process of rehabilitation of degraded hills.

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